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Recent Advances in Spacecraft Charging

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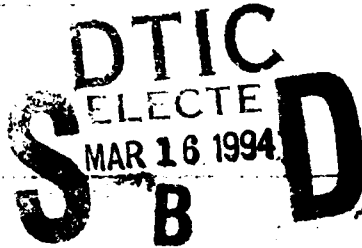
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This is an overview on advances achieved in the past decade on spacecraft charging. The topics discussed are the failures of SC2, the bootstrap, asymmetric potential, critical temperature, triple-root potentials, sheath engulfment, charging in wakes, supercharging, sheath ionization, beam emission for mitigation of charging, and anomalies.

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Recent Advances in Spacecraft Charging

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ABSTRACT

This is an overview on advances achieved in the past decade on spacecraft charging. The topics discussed are the failures of SC2, the bootstrap, asymmetric potential, critical temperature, triple-root potentials, sheath engulfment, charging in wakes, supercharging, sheath ionization, beam emission for mitigation of charging, and anomalies.

INTRODUCTION

Garrett [1981] and Whipple [1981] reviewed the state of spacecraft charging a decade ago. Since then, there have been many advances in this field. This review continues from where Garrett and Whipple left off. We confine our scope to basic theories and experiments rather than detailed computational modeling, statistical observational data, instrumentation, applications, or standards. In a short review, some author citations and important advances are left out inevitably.

THE FAILURES OF SC2

The most catastrophic event on the SCATHA satellite was probably the failures of the SC2 devices. On March 30, 1979, an electron beam of 3 keV and 13 mA was emitted from SCATHA. Differential charging over 2 kV occurred. A few seconds later, SC2-1, a device for measuring potentials, failed. The device was at the tip of a 3 m boom. At the moment of the failure, the boom was about 1/3 in sunlight and 2/3 in the shadow of the satellite. Half of a satellite spin period later, SC2-2, a similar device on the tip of a diametrically opposite boom, failed.

This event has been documented by Cohen *et al* [1981]. While the cause of the failures is unknown, they serve as alarming examples of the adverse effects of spacecraft charging.

THE BOOTSTRAP

Although the fundamentals of charging of surfaces were well known in the 1970's, calculations were confined to charging of single surfaces only. For spacecraft with many different surface materials, the calculation of the potential of each surface with respect to the ambient plasma by ignoring the potentials of the adjacent surfaces may yield inaccurate results. The neglect of mutual interactions is analogous to the neglect of Vlasov terms in a plasma.

Katz *et al* [1982] advanced a method, the bootstrap, which calculates surface potentials in a self-consistent manner. The method is useful when high differential charging occurs.

With differential charging, the outgoing secondary electrons may not leave completely or may land on another surface. There may even be potential contours hanging over part of an adjacent surface (Fig. 1). Furthermore, the incoming electron trajectories may be deflected. As a result, one has to recalculate the potentials, taking into account the modification of outgoing and incoming electron fluxes. If computer time is available, one should continue iterating until a steady configuration of potentials ensues.

ASYMMETRIC POTENTIALS

Besides differences in surface material properties, an important cause of differential charging is the asymmetry of the natural environment. For example, ambient electron fluxes

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with preferential directions are prominent in stormy periods [Saflekos, *et al.*, 1981] and in polar regions [Besse, *et al.*, 1984]. Charging in the polar region in low earth orbits is now an important concern and major studies are underway [Katz, *et al.*, 1989]. Magnetic field effects on spacecraft charging are important in low earth orbits [Laframboise, 1988]. At the geosynchronous environment, the induced electric field $V \times B$ is small compared with typical electric fields on charged surfaces.

Sunlight is an important factor of asymmetry. Besse and Rubin [1980] offered a simple, but useful, dipole model (Fig. 2).

$$\epsilon\phi(r, \theta) = K \left(\frac{1}{r} - \frac{A \cos \theta}{r^2} \right) \quad (1)$$

where r , θ are polar coordinates, and K , A are monopole and dipole parameters. The dipole model not only accounts for the main features of asymmetrical potential distribution of a sunlit spacecraft with insulated surfaces but also predicts, as a result of the dipole field, trapping of photoelectrons by a potential barrier on the sunlit side (Fig. 2).

CRITICAL TEMPERATURE

Lai *et al.* [1982] and Laframboise *et al.* [1982] discovered a fundamental concept, viz., the critical (or threshold) temperature T_c of ambient electrons for high negative charging. They proved mathematically that there exists a critical electron temperature T_c for a given surface material in a Maxwellian model of space plasma. When the ambient electron temperature exceeds T_c , high negative charging occurs.

The concept is based on current balance. When a primary electron hits a surface, secondary and backscattered electrons may leave. If the incoming flux exceeds the outgoing flux, negative charging occurs. Since high energy primary electrons (keVs or higher) penetrate deeper into a surface material, they may generate less outgoing flux than low energy ones (hundreds of eVs). This is why high temperature ambient plasma environments favor negative charging. There exists a critical

temperature T_c for a given material.

The ratio of outgoing to incoming electron fluxes for a surface in a Maxwellian plasma is [Lai, *et al.* 1983]

$$\frac{\int_0^\infty dE E (\delta(E) + \eta(E)) \exp(-E/kT)}{\int_0^\infty dE E \exp(-E/kT)} - 1 \quad (2)$$

where δ and η are the secondary and backscattered emission coefficients. The solution of eq(2) is the critical temperature T_c [Table 1].

Details of the concept have been reported by Laframboise *et al.* [1982] and Lai *et al.* [1983]. The authors have listed useful tables of critical temperatures for various materials. The tables may be useful for spacecraft designers who wish to avoid or to achieve spacecraft charging. A review on this subject has been given by Lai [1991b].

TRIPLE-ROOT POTENTIALS

The triple-root (TR) jump in surface potential may cause a sudden development of high level differential charging. Whipple [1965] and Laframboise [1979] made pioneering contributions to the TR theory. Besse [1980] constructed a simple dynamic model, which not only demonstrates the TR behavior but also clarifies the roles played by the double Maxwellian space plasma in a TR situation. Hastings [1986] suggested the use of electrostatic noise to trigger small jumps in order to avoid sudden large triple-root jumps in potential.

The idea of TR is simple. Figure 3 shows a general feature of the flux-potential $J(\phi)$ curve [Lai, 1991b]. At large negative ϕ , the slope $dJ(\phi)/d\phi$ is negative because, as the magnitude of $\phi(<0)$ increases, the incoming ion flux increases. Thus, at sufficiently large magnitude of $\phi(<0)$, J is positive and features a negative slope. At positive ϕ , the outgoing electrons are attracted by the surface. Thus, at sufficiently large magnitude of $\phi(>0)$, J is negative and again features a negative slope. Mathematically, the curve must cross the $J=0$ line an odd number of times in between the two slope regimes, thus forming an odd number of roots. The even numbered roots are unstable because the slope

at any of these roots is positive, resembling an Ohm's law with a negative resistance. Thus, one can state a general theorem: "In a general flux-voltage curve $J(\phi)$, there must be odd number of roots $J(\phi)=0$ and only the odd numbered roots are stable". The root counts can start from either the right or the left hand side.

As the environment changes in time, the $J(\phi)$ curve changes. As a result, the number of roots may change. It must change by an even number according to the general theorem. Thus, if the potential is initially at a certain root, which disappears as the environment changes, a neighboring root must also disappear simultaneously. Therefore, the potential jumps to a neighboring odd root (Fig. 4).

The first observation of TR in the laboratory was reported by *Nam et al.* [1987]. *Lai* [1988, 1991a] derived the parametric domains (Fig. 5) of the TR behavior in the double Maxwellian plasma model. Using the domains, one can predict when a TR jump in spacecraft potential should occur. One such example [*Lai*, 1988, 1991a] is the prediction that a TR jump should have occurred on the SCATHA satellite on Day 114, 1979. Upon examination, the SCATHA data did show a jump in potential with the correct magnitude and sign reversal at the right condition as predicted. This agreement between theory and observation strongly suggests (but does not confirm) that a TR jump occurred in space. If the event was really a TR jump, it would be the first observation of its occurrence in space.

Interestingly, the critical temperature T_c also plays an important role (Fig. 5) in the domains [*Lai*, 1991a] and hysteresis [*Lai*, 1991b] of TR potential jumps for the double Maxwellian model of space plasma.

SHEATH ENGULFMENT

Multi-body interaction is a new development in the past decade. When the potential of a spacecraft body or surface increases, its sheath extends. Eventually, the sheath may engulf another surface of very different potential (Fig. 6). The electrons emitted from one surface may be attracted towards

the one with a relatively positive potential. *Lai* [1987] has derived formulae for the spacecraft sheath engulfment of long booms attached to a rotating spacecraft in sunlight. He calculated the resultant potentials due to the photoelectron flow from the SC10 booms to the SCATHA satellite body [*Lai*, 1987, 1994]. *Katz et al.* [1989] showed computer simulations of high potential sheath engulfment and used the simulation results to interpret the results obtained on SPEAR-1.

CHARGING IN WAKES

Ion depletion in the spacecraft wake was measured in the early sixties [*Bourdeau and Donley*, 1964; *Samir and Wilmore*, 1964]. In recent years, there has been interest on the charging of a small object, such as an astronaut or a short tether, in the plasma wake of a large spacecraft in low earth orbit.

Gurevich et al. [1969] gave a complicated analytical expression for the current density as a function of angle. *Rubin and Besse* [1986] gave a simple model for the charging of a small sphere in the far wake of a large spacecraft. The model is based on the orbit-limiting Langmuir probe idea. Suppose the ions at rest in the ionosphere have a velocity V in the spacecraft frame. For a spacecraft of radius R (Fig. 7), the ion orbit grazes the small object of radius a in the wake if

$$R^2 - a^2 \left(1 - \frac{2q\phi}{mV^2} \right) \quad (3)$$

where m is the ion mass, q the ion charge, and ϕ the potential of the object. That is

$$-q\phi = \frac{1}{2} m V^2 \left(\frac{R^2}{a^2} - 1 \right) \quad (4)$$

This is the voltage to which the object will charge before it is able to attract ions from the inner edge of the Mach cone. Taking $R = 15$ m, $a = 1$ m, and an O^+ ion energy of 6 eV, *Rubin and Besse* [1986] obtained a potential of -1344 V. This is a threshold. As the negative potential rises above this value, a copious current of ionospheric ions is available for neutralization. Therefore, the object will charge

almost precisely to the threshold value.

Observations have confirmed the existence of plasma wakes behind spacecraft [for example, *Samir, et al.*, 1986]. Many authors have simulated details of wake charging on the computer and in the laboratory [for example, *Martin*, 1974; *Soubeyran, et al.*, 1989; *Wang*, 1992; *Enloe, et al.*, 1993].

SUPERCHARGING

Supercharging is a new discovery in the past decade. It is a phenomenon in which a spacecraft is charged to a potential higher than the energy of the electron beam emitted. The old thinking, "a spacecraft can only charge as high as the beam energy only" in analogy to "one can only dig as deep as one can throw" (Fig. 8), is now discarded.

In at least three events, supercharging was observed [*Kochmaryov*, 1985; *Maehlum*, 1988; *Managadze*, 1988; *Denig, et al.*, 1991]. There are theories based on beam-plasma fluctuations [for example, *Mandell and Katz*, 1989; *Winglee*, 1991]. It appears that supercharging occurs at equilibrium. Recently, *Lai* [1993] gave a preliminary report on a steady state theory based on beam divergence. The transverse energy gained by a diverging beam electron in a supercharging situation can be of the order of the beam energy. The angular momentum may prevent the electron from returning to the spacecraft.

SHEATH IONIZATION

Sheath ionization is a phenomenon in which beam electrons returning to a spacecraft may ionize the neutral gas in the sheath surrounding the spacecraft (Fig. 9). The ionization modifies the charge density in the sheath and lowers the spacecraft potential. A numerical model of sheath ionization by *Lai, et al.* [1982] predicted a non-monotonic behavior: the potential goes up as the beam current increases initially but goes down when a critical current is exceeded (Fig. 10). This non-monotonic behavior was observed in the BERT-1 experiment [*Lai*, 1992] as predicted.

There is an interesting aspect of sheath ionization. When abundant ionization occurs, the

sheath may expand as demonstrated by computer simulations [*Cooke*, 1987].

Sheath ionization is probably a fairly common phenomenon when electron beams are emitted from spacecraft in the ionosphere. It is important when the ambient neutral gas density is high, or when the outgassing is significant. It also occurs during simultaneous electron and neutral beam emissions in the ionosphere. When sheath ionization occurs, an excitation glow can be observed in the vicinity of the spacecraft.

SPACECRAFT DISCHARGING

There are two aspects of spacecraft discharging. One aspect is discharging as a mitigation of charging. Another aspect is sudden discharging as a probable cause of onboard electronic instrument anomalies.

1. Mitigation

Electron and ion beams have been emitted to mitigate positive and negative charging respectively, with partial successes [*Cohen, et al.*, 1981; *Cohen and Lai*, 1982; *Olsen*, 1985; *Werner*, 1988]. When the beam current is lower than the ambient current, the latter controls the charging. When the beam energy is low, partial beam return may occur.

Paradoxically, when a low energy ion beam is emitted from a negatively charged spacecraft, the level of charging decreases [*Cohen and Lai*, 1982]. Also, when electron and ion beams (or a plasma beam) are emitted together, the efficiency of discharging is enhanced [*Cohen et al.*, 1981].

Lai [1989] explained both phenomena by suggesting that the ions return to the "hot spots" thereby neutralizing the negative potentials. The ions may also generate secondary electrons which carry away the negative charges (Fig. 11).

2. Anomalies

Spacecraft discharging mechanisms proposed in the 1970's were based on the possibility of a secondary emission avalanche [*Balmain*, 1978; *Inouye*, 1980]. In recent years, the emphasis is shifted to the

ionization of neutral gas inside dielectrics, on the surface, or in the vicinity of highly and differentially charged spots.

Laboratory experiments [Frederickson, *et al.*, 1983; 1992] suggested that when an initially small discharge occurs in a surface crack, for example, a small amount of plasma and neutral gas would be generated from inside the crack. Ionization of the neutral gas may lead to a chain reaction discharge propagating to a larger area. The discharge current due to gas ionization is believed to be much higher than that from secondary electron avalanche.

Anomalies on CRRES seem to support the idea of deep dielectric discharging accompanied with further ionization of the partially ionized gas released from the dielectrics [Frederickson, *et al.*, 1992; Violet and Frederickson, 1993]. It is astonishing that all of the CRRES anomalies reported occurred when there was little or no spacecraft charging at the outside of the CRRES. Frederickson [1993] proposes that CRRES anomalies may have occurred in cables and on other insulators inside the satellite behind the thermal blankets.

This suggests that even at high altitudes and without normal outgassing, ionization of the neutral gas liberated inside or outside a spacecraft may be an important mechanism for rapid spacecraft discharging.

As a speculation, the anomalies might be caused by deep dielectric charging with layers of alternate signs of charges so that there is little or no apparent charging on the surface. An unstable equilibrium exists until a small force (such as an ionization track by a high energy proton from space, severe temperature variation, or charge migration a la Frenkel along susceptible trails, or desorption of neutral gas from cracks) triggers a discharge inside the spacecraft (Fig. 12).

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TABLE 1. CRITICAL TEMPERATURES (eV)

MATERIAL	ISOTROPIC	NORMAL
Aluminium	600	---
Aluminium Oxide	1900	1200
Cu-Be	2100	1300
Cu-Be(Activated)	5300	3700
Gold	4900	2900
Indium Oxide	3600	2000
Kapton	800	500
MgF ₂	10900	7800
Magnesium	400	---
Magnesium Oxide	3600	2500
Silver	2700	1200
SiO ₂	2600	1700
Teflon	2100	1400

[Lai, *et al*, 1983]

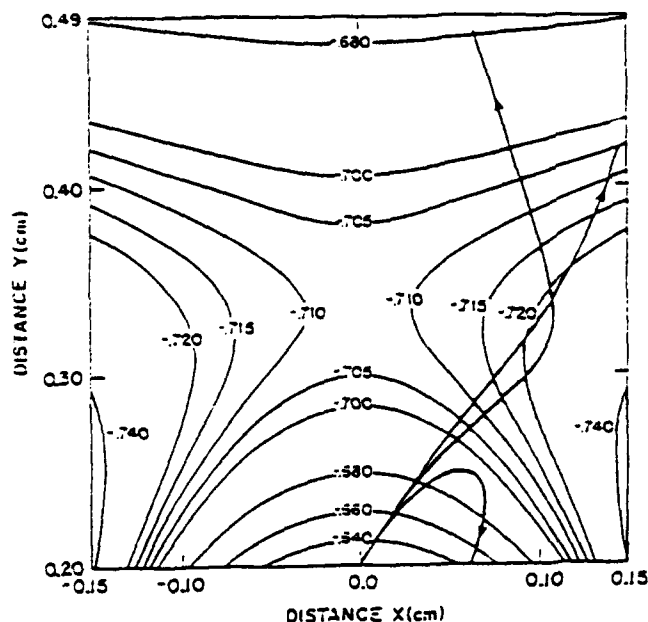


Fig.1. An example of (negative) potential contours overhanging from neighboring surfaces. The middle surface is at $-0.2 < x < 0.2$; $y=0$. The trajectories show that electrons emitted from (0,0.2) may return or deflected, depending on their energies and angles.

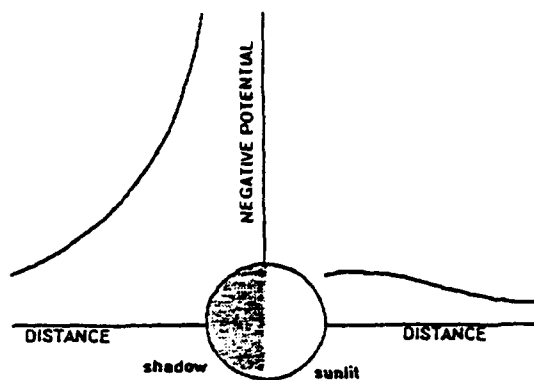


Fig.2. Potentials of the monopole-dipole model [adapted from Besse and Rubin, 1981]. As a result of photoemission, the potential on the sunlit surface is positive relative to that on the shadow side, even though both potentials are negative relative to the ambient plasma. The model shows a potential barrier on the sunlit side.

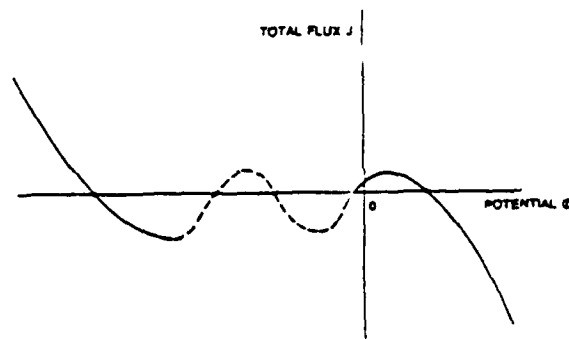


Fig.3. A general flux-potential curve [Lai, 1991b]. The total number of roots, $J(\phi)=0$, must be odd.

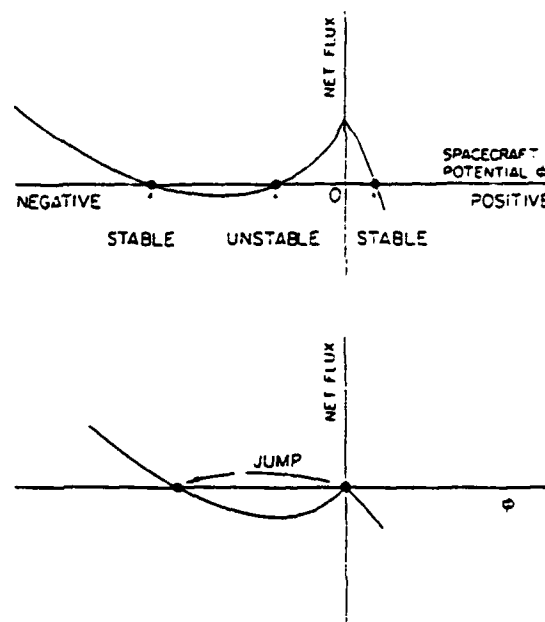


Fig.4. An example of triple-roots [Lai, 1991a]. As the space environment changes, the curve may move up or down. As a result, two of the roots may coalesce and then disappear. If the potential is at a root that is disappearing, it jumps to a neighboring root.

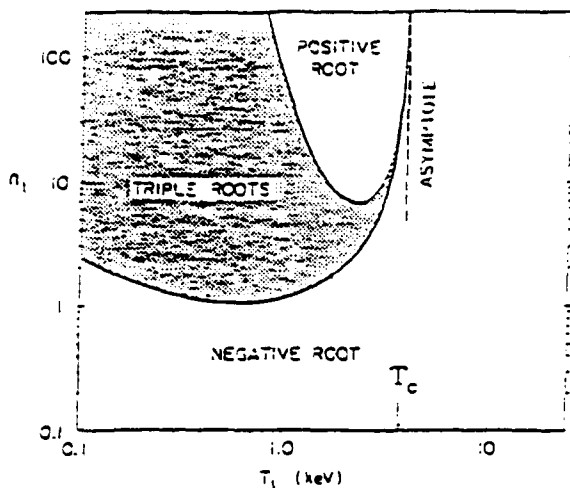


Fig.5. The triple-root domain for copper-beryllium in the double Maxwellian space environment of Day 114, 1979. The domain asymptote is located at the critical temperature T_c . [Lai, 1991b].

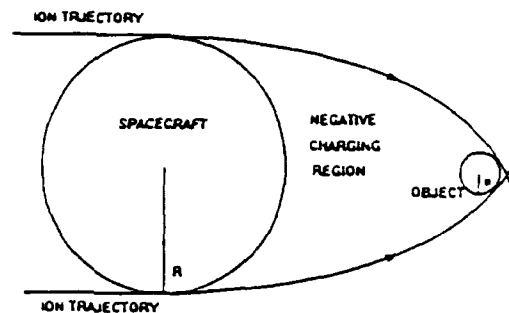


Fig.7 Negative charging in a spacecraft wake.

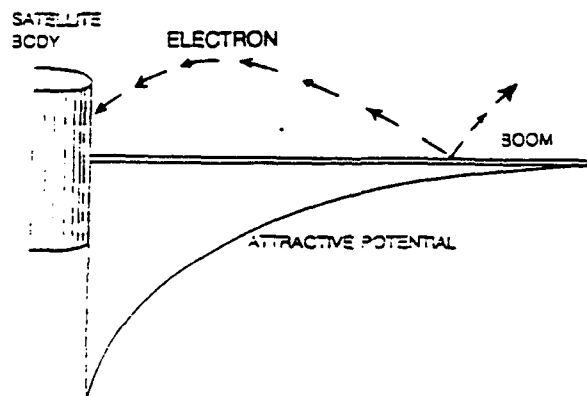


Fig.6. An example sheath engulfment. If the positive potential of the satellite body increases, an increasingly large portion of the boom becomes engulfed in the potential well, attracting electrons from the booms to the body.

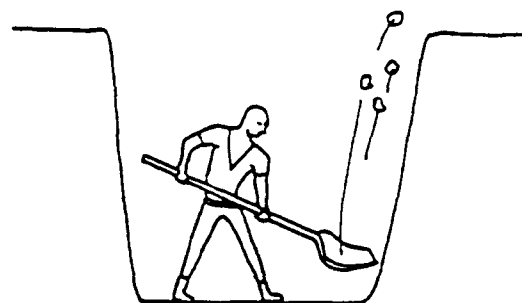


Fig.8 An analogy: "One can dig as deep as one can throw". It was commonly thought that a spacecraft can charge only as high as the energy of the beam emitted.

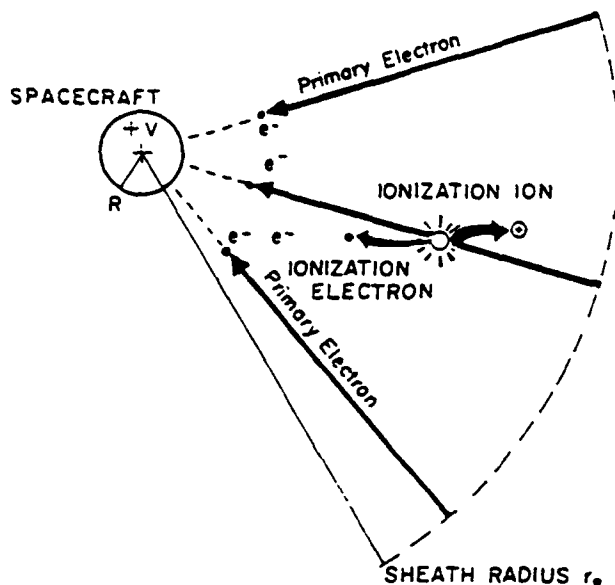


Fig.9 Sheath ionization. As the electrons are attracted towards the spacecraft, they may ionize the neutral gas resulting in new ions and electrons.

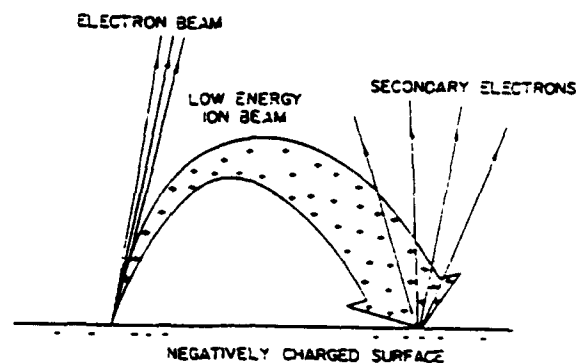


Figure 11. Low energy plasma beam emission from spacecraft for mitigation of negative charging. While the electrons carry away negative charge, the ions return to the "hot" spots, not only neutralizing the negative charge but also generating secondary electrons which carry away more negative charge [Lai, 1989].

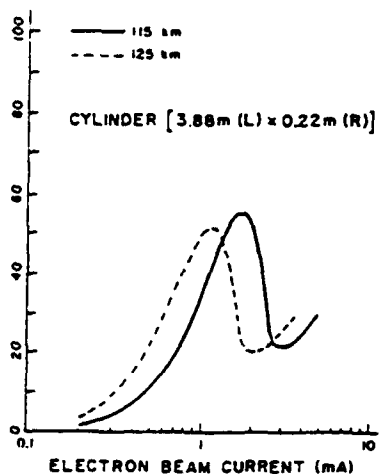


Fig.10. Computed non-monotonic current voltage behavior for a cylindrical spacecraft [Lai, 1992].

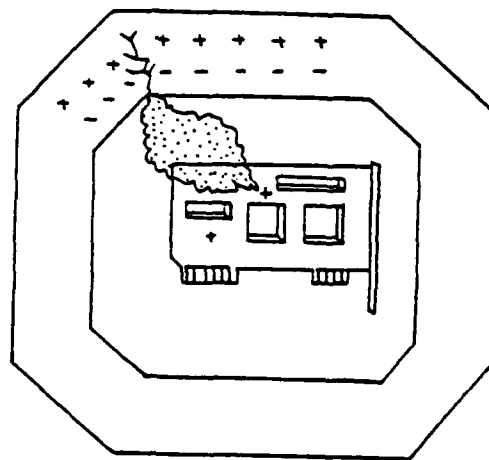


Figure 12. A concept of discharging inside a spacecraft. A high potential may not be detected on the surface outside. Layers of charges inside the dielectric material may exist. A high potential may exist between the electronics and a local area of the inner surface. The gas from narrow cracks, if ionized, may produce a large current pulse causing circuit anomalies.